



Kennedy Engineering Academy Accelerated Training Program Showcase

“Design of the Core Stage Inter-Tank Umbilical (CSITU) Compliance Mechanism”

Kurt Smith

NE-M2 Structures & Mechanisms Design

01-09-2013

Background



- Born in Daytona Beach, FL
- Raised in Knoxville, TN
- Graduated from Powell High School



College



<http://www.sercc.com>

- Tennessee Technological University
- Graduated May 2012
- Bachelor of Science: Mechanical Engineering

Previous NASA Experience

Internship, Marshall Space Flight Center, Fall 2009

- Undergraduate Student Research Program (USRP)

Co-op, Kennedy Space Center, Spring 2010, Summer 2012

- Co-op Program





ATP Overview



Supervisor: Joe Porta

Mentor: Patrick Maloney

Branch: NE-M2, Structures & Mechanisms Design Branch

Topics Covered:

- I. Required Reading
- II. Diverse Work Assignments
- III. Targeted Work Assignments
- IV. Final Project

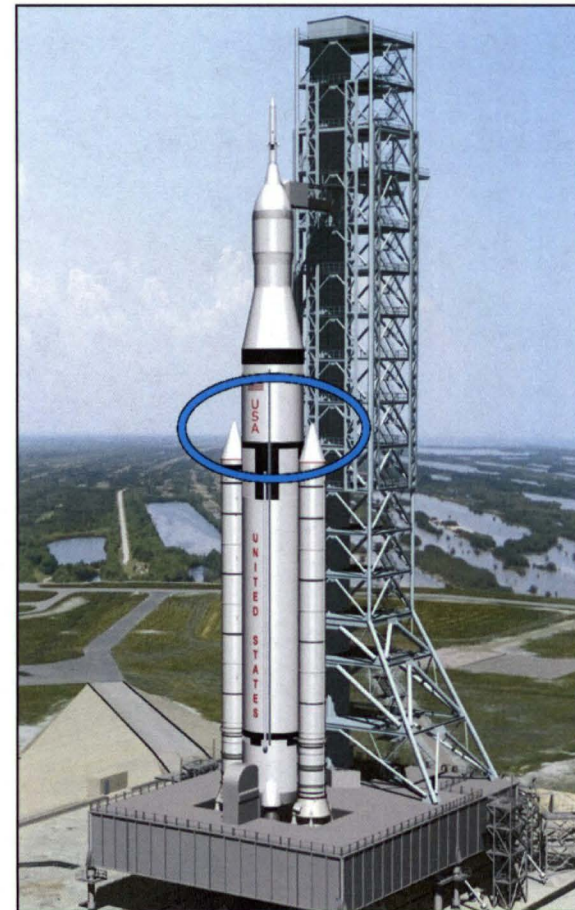
Design of the Core Stage Inter-Tank Umbilical (CSITU) Compliance Mechanism

Project Goals

- Design the compliance mechanism for the CSITU system to a 30% level
 - 3D models completed in Pro/Engineer
 - Relevant design analysis
- Must meet all system requirements and establish basis for proceeding with detailed design

Tasks to be completed

- A design that meets requirements for the 30% design review, 01/16/2013



Umbilical Background

Umbilical arms provide commodities to the launch vehicle prior to T-0. Commodities can range anywhere from hydraulics, pneumatics, cryogenic, electrical, ECS, etc...

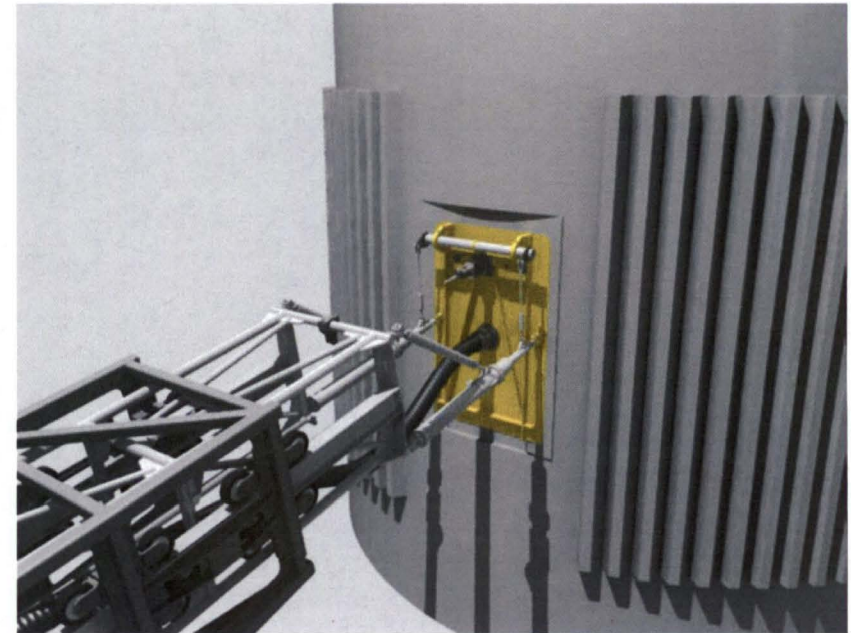
- Umbilicals commonly employ truss structures to deliver commodities to vehicle
- Common configurations include:
 - Tilt-up
 - Swing Arm
 - Hose Drape
 - Drop Arm
- Umbilical arms will be mounted to Mobile Launch Platform
- SLS currently has 9 T-0 umbilical arms



The compliance refers to the ability of the umbilical to adjust to minor changes in vehicle location.

The compliance mechanism refers to the mechanism on the ground support equipment (GSE) that compensates for these changes. For the CSITU, these minor changes, or vehicle excursions, can be up to ± 4 in.

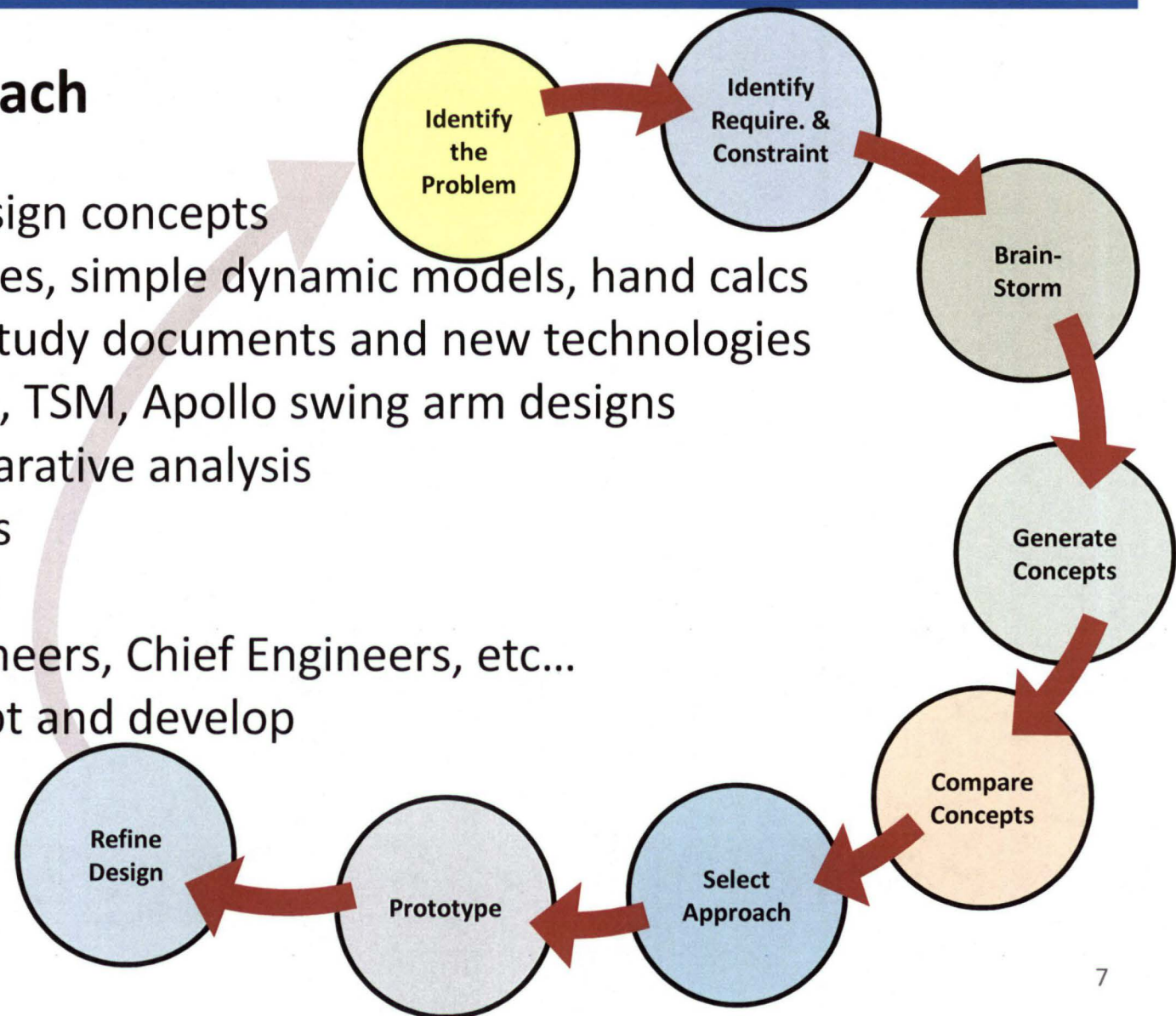
- Excursions refer to movements of the vehicle caused by wind loads and thermal expansion
- It is ideal to have significant vertical compliance so a passive secondary release mechanism may be implemented



Example of compliance for Tilt-Up Umbilical Arm (TUUA)

Project Approach

- Brainstorm design concepts
 - Create sketches, simple dynamic models, hand calcs
- Review trade study documents and new technologies
 - Review TUUA, TSM, Apollo swing arm designs
- Create a comparative analysis
 - List Pros/Cons
- Gain Feedback
 - Mentor, Engineers, Chief Engineers, etc...
- Choose concept and develop



General & CSITU Specific Requirements

1,500 lb and 36" wide x 48" long ground plate
+/- 4.0" in Z-axis (orthogonal to tower face)
+/- 2.0" in Y-axis (parallel to tower face)
+0.5"/-2.0" in X-axis (vertical)
10,000 lb maximum loads in to vehicle
Blast Load: 8 psi vertical, 4 psi horizontal.

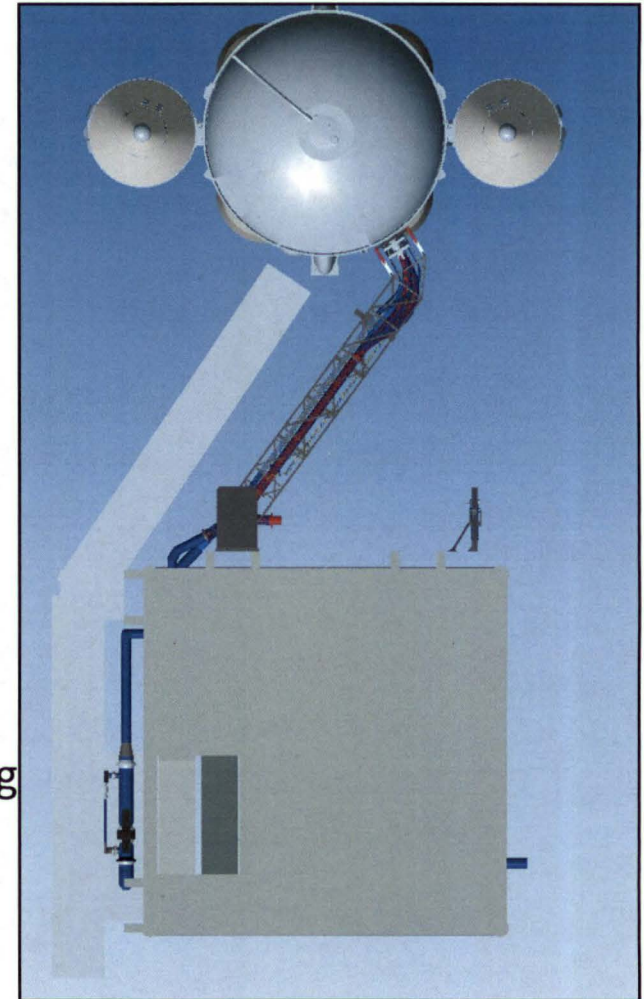


Design Criteria

Mechanism must allow ground plate to rotate 10°
At least 12" of retract distance at closest point to vehicle
Design shall include provisions to prevent binding, jamming, or seizing
Capability for easy ground plate manipulation when mating to vehicle
Repeatable retract position at launch

Design Considerations

- How compliant is it
- Primary/Secondary disconnect
- Primary/Secondary retract method
- Retract distance
- Commodity line routing
 - Mechanism must leave room for commodities
 - What kinds of bends will the lines be making?
- Stiffness of commodity lines
 - Changes center of gravity of plate
 - Effects passive secondary disconnect system
- Rotating vs. Translating surfaces
 - Translating surfaces more susceptible to binding
 - Prefer redundant rotating surfaces over redundant translating



Tilt Up Umbilical Arm (TUUA) Prototype

LH2 Tilt Up Umbilical Arm is shown below. The compliance mechanism includes 4 struts, a translating truss, and a rotating truss.

PROS

Testing in progress

Achieves excursion requirements

Struts are already designed for smaller TUUA plate

CONS

Translating surfaces susceptible to binding

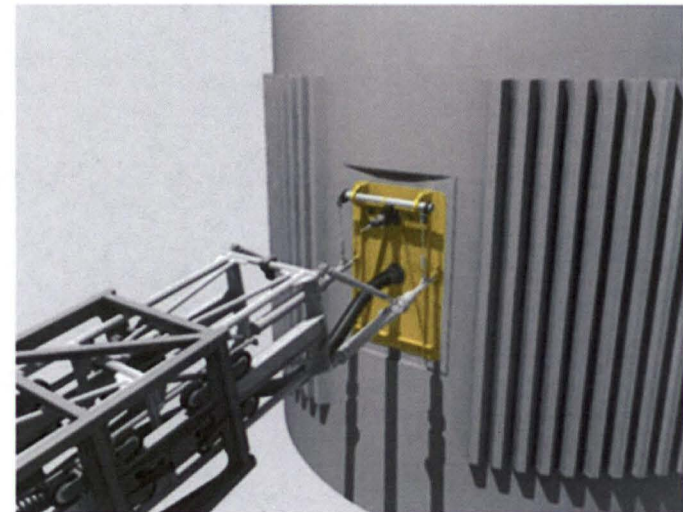
Complex strut design with tight tolerances

TUUA configuration different from CSITU (swing arm)

Struts not designed for vertical compliance

SPRING RATES

Springs in diagonal struts calculated to be 1414 lbf for CSITU



Example of compliance for Tilt-Up Umbilical Arm (TUUA)

Draped Configuration

Drape is a common configuration(OSMU, ICPSU)

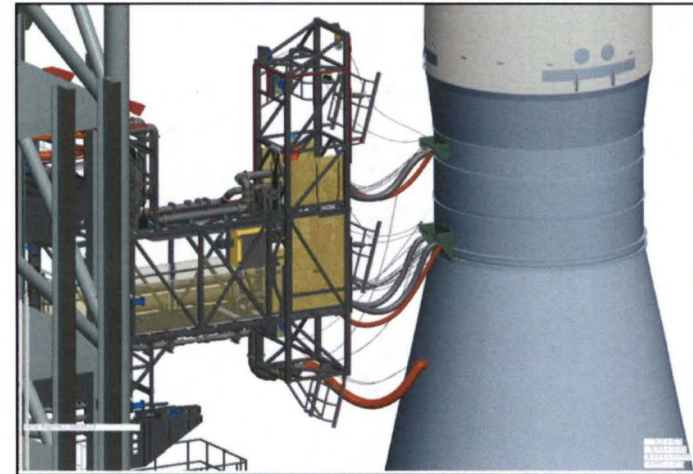
PROS

Compliant in all directions

CONS

GSE for mating operation

CSITU has 1500 lb ground plate at retract



ICPSU

Tail Service Mast (TSM)

Have been used for Apollo and Shuttle

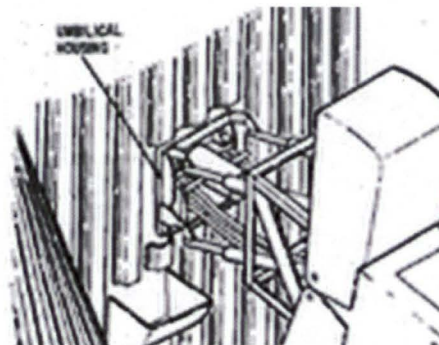
PROS

Long record of reliability

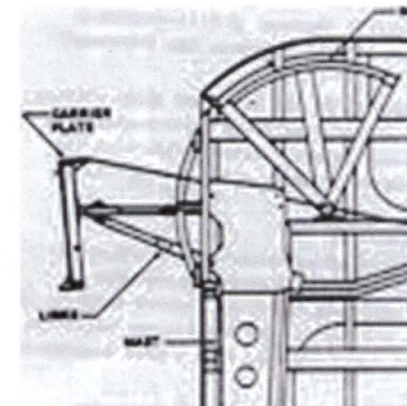
Plates for Shuttle ≈1600 lb

CONS

TSM tilt-up vs. CSITU swing arm



Saturn V TSM



Shuttle TSM

Scissor Link with Translating Mechanism at Plate

- Scissor link accommodates excursions in the y and z
- Translating mechanism achieves x excursions

PROS

- Achieves excursions requirements
- Rotating surfaces

CONS

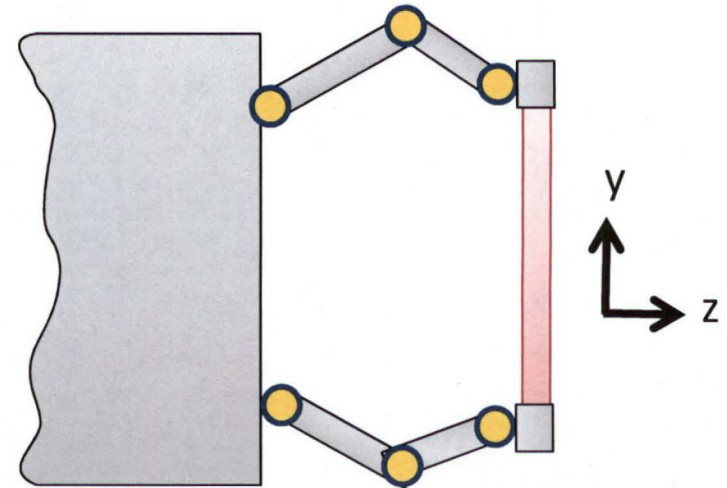
- Translating surfaces susceptible to binding
- Limited vertical compliance
- Large moment load on pins at truss

SPRING RATES

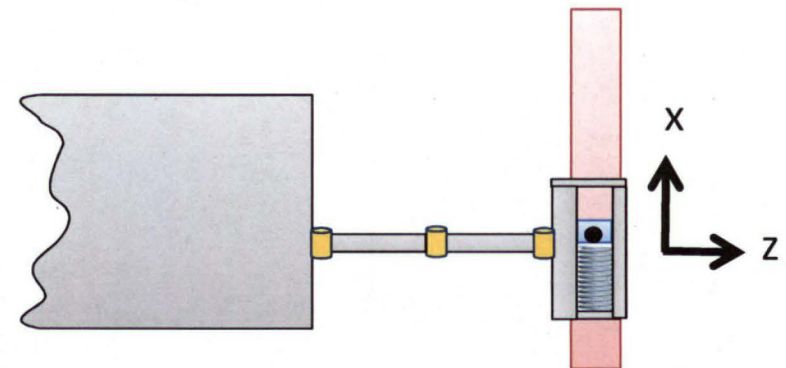
Springs at ground plate calculated to be 500 lbf

MOMENTS

Moment at truss is 48,000 in·lbf



TOP VIEW



SIDE VIEW

Concept #2

Scissor Link with Struts

- Scissor Mechanism has universal joints at truss
- Spring loaded struts provide nominal plate location

PROS

Achieves excursions requirements
Rotating surfaces

CONS

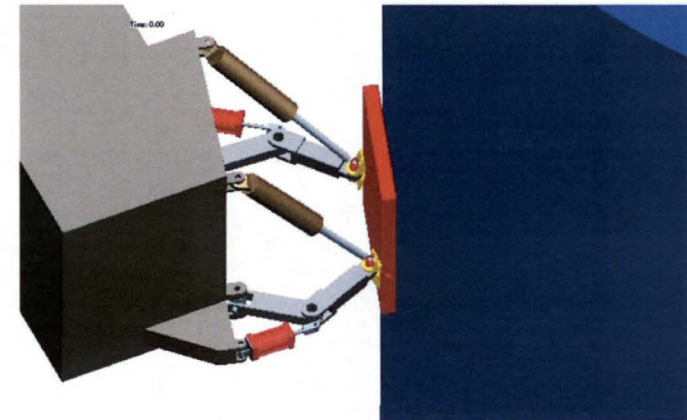
Translating surfaces susceptible to binding

DYNAMICS

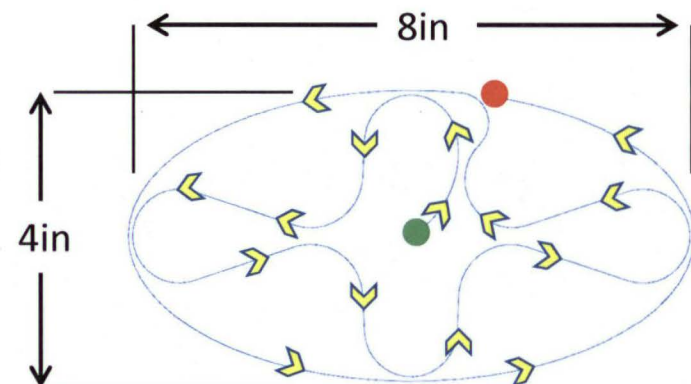
Model created in Pro/E Mechanism to simulate mechanism movement through worse case vehicle excursions (right). This is useful for characterizing mechanism behavior.

SPRING RATES

Springs in struts calculated to be 708 lbf



Mechanism Excursions Animation



Excursion Path for Animation

Controlled Manipulator Arms

- Derived from industrial manipulators, common in production
- Uses pneumatic/hydraulic cylinders to offload weight
- Allows for easy handling of object
- Rotating pedestal is optional

PROS

Achieves excursions requirements

Rotating surfaces

Easy operator manipulation

CONS

Complex control system for cylinders

Potential for mechanism to lock up (failure of control system or cylinder binding)

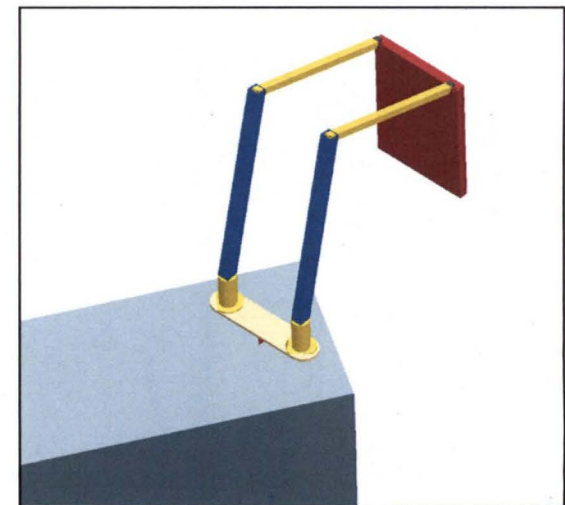
PNEUMATIC/HYDRAULIC SIZING

Aft cylinder estimated to be 3215 lbf

Forward cylinder estimated to be 2500 lbf



<http://www.mdphandling.com/industrial-manipulator/industrial-manipulator.php>



Passive Manipulator Arms, *from Tariq Rahman, Ph.D in document "A Simple Technique to Passively Gravity-Balance Articulated Mechanisms"*

- Uses springs to passively balance four bar linkages
- Linkage is balanced in all positions

PROS

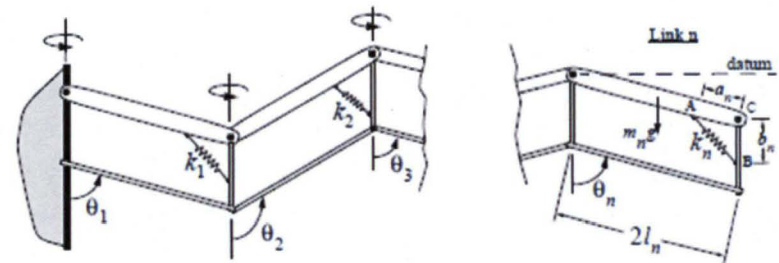
- Achieves excursions requirements
- All Rotating Surfaces
- Easy operator manipulation
- Reduces retract actuator size
- No actuators used for linkage control

CONS

- Change in plate mass will change spring rates

SPRING RATES

- Initial calculations estimated springs to be about 300 lbf



Credit: Tariq Rahman, Ph.D



Desktop Prototype

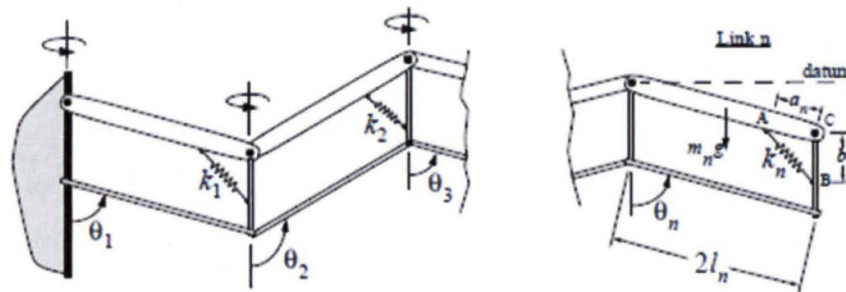
Concept #3B, Passively Gravity Balanced Linkage

After completing the comparative analysis, this design was chosen.

- Use of rotating surfaces
 - Increased reliability
- Allows for operator manipulation
 - Require no extra GSE for mating
- Repeatable retract position after launch
- Meets vehicle excursion requirements
- Allows sufficient compliance to accommodate a secondary release actuated by vehicle rise



Desktop Prototype



Credit: Tariq Rahman, Ph.D

Using the conservation of energy method, springs rates can be calculated to achieve a balanced system.

For a static analysis, kinetic energy = 0 and potential energy is constant.

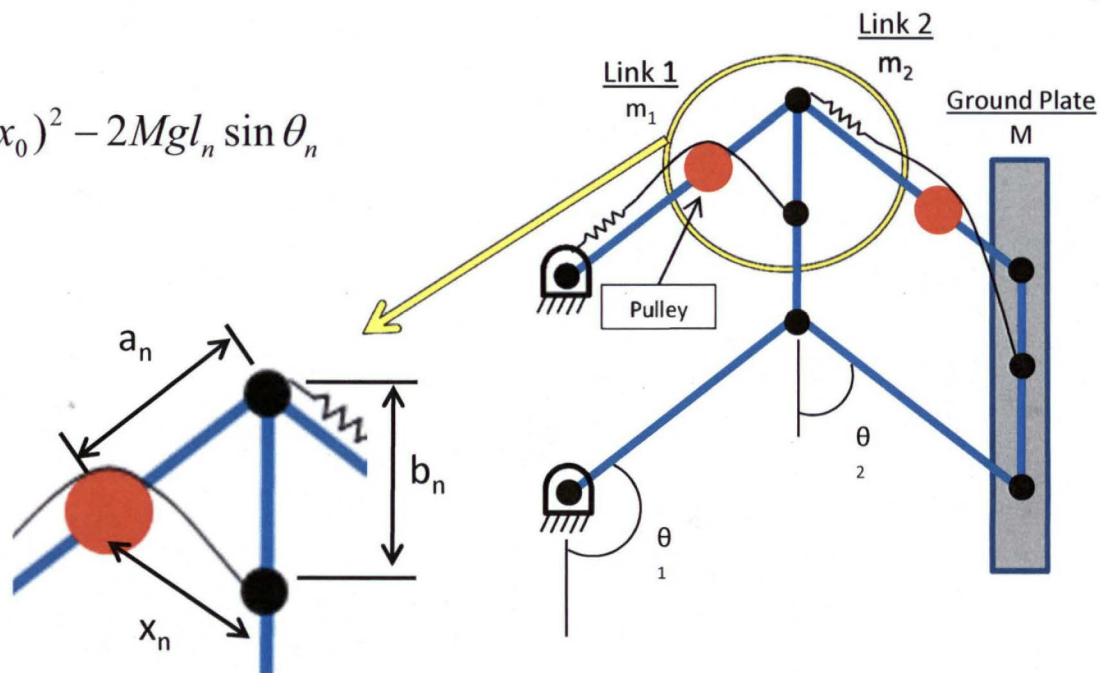
*Assume supporting links are massless and free length of spring is zero ($x_0=0$). This is accomplished by moving the spring and adding a pulley and wire at these locations.

$$\frac{\partial}{\partial \theta_n}(PE) = 0$$

$$PE_n = -m_n g l_n \cos \theta_n + \left(\frac{K_n}{2}\right)(x_n - x_0)^2 - 2M g l_n \sin \theta_n$$

Using law of cosines and setting $x_0=0$,

$$x_n^2 = a_n^2 + b_n^2 + 2a_n b_n \cos \theta_n$$



Substitute into potential energy equation,

$$PE_n = -m_n g l_n \cos \theta_n + \left(\frac{K_n}{2}\right)(a_n^2 + b_n^2 + 2a_n b_n \cos \theta_n)^2 - 2M g l_n \sin \theta_n$$

Take partial derivative of potential energy equation,

$$\frac{\partial}{\partial \theta_n}(PE) = m_n g l_n \sin \theta_n - K_n a_n b_n \sin \theta_n + 2m g l_n \sin \theta_n = 0$$

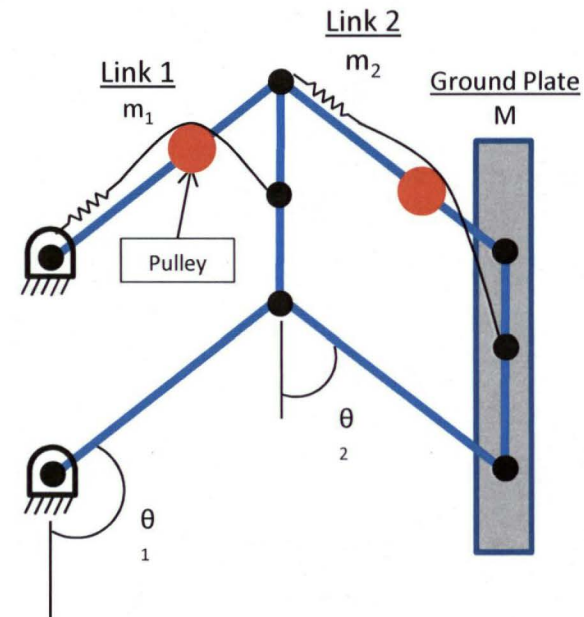
Solve for K_n ,

$$K_n = \frac{g l_2}{a_2 b_2} (m_2 + 2M)$$

The same method can be used to find K_{n-1}

The resulting spring rates are:

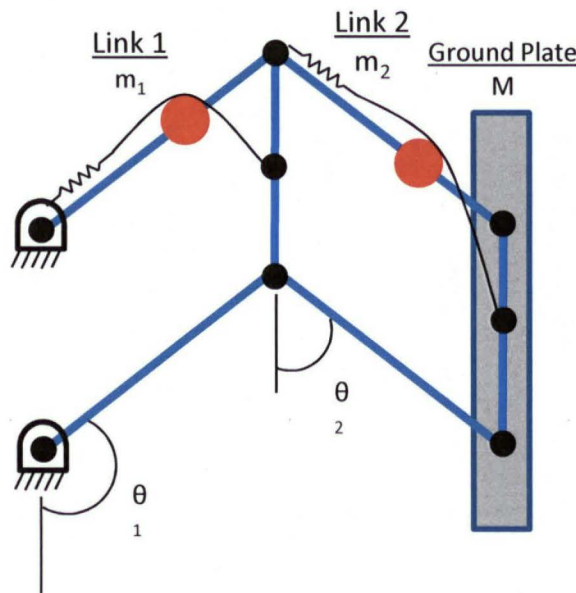
$$K_2 = \frac{g l_2}{a_2 b_2} (m_2 + 2M) \quad K_1 = \frac{g l_1}{a_1 b_1} (l_1 m_1 + 2l_2 m_2 + 2l_2 M)$$



Concept #3B Spring Rates

A study was done to determine the sensitivity of the spring rates to the ground plate mass (M).

Model Parameters							
m_1	m_2	l_1	l_2	a_1	b_1	a_2	b_2
50	30	11.5	11.5	6.5	7.5	6.5	7.5

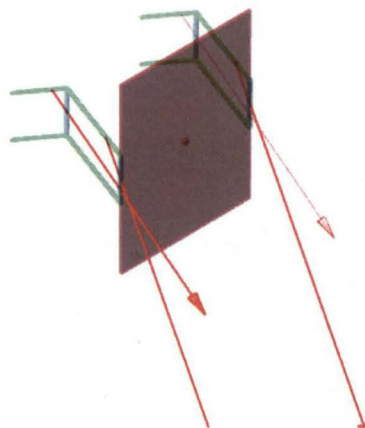


Results		
M	K_1	K_2
1480	375.08	356.21
1485	376.26	357.38
1490	377.44	358.56
1495	378.62	359.74
1500	379.80	360.92
1505	380.97	362.10
1510	382.15	363.28
1515	383.33	364.46
1520	384.51	365.64

From the results, a change of 40 lbm saw 2.6% change in required spring rates

A Dynamic model was created in Adams to simulate the compliance dynamics. This is useful for determining spring rates, joint loads, expected mechanism behavior, etc...

Last_Run Time= 0.0000 Frame=001

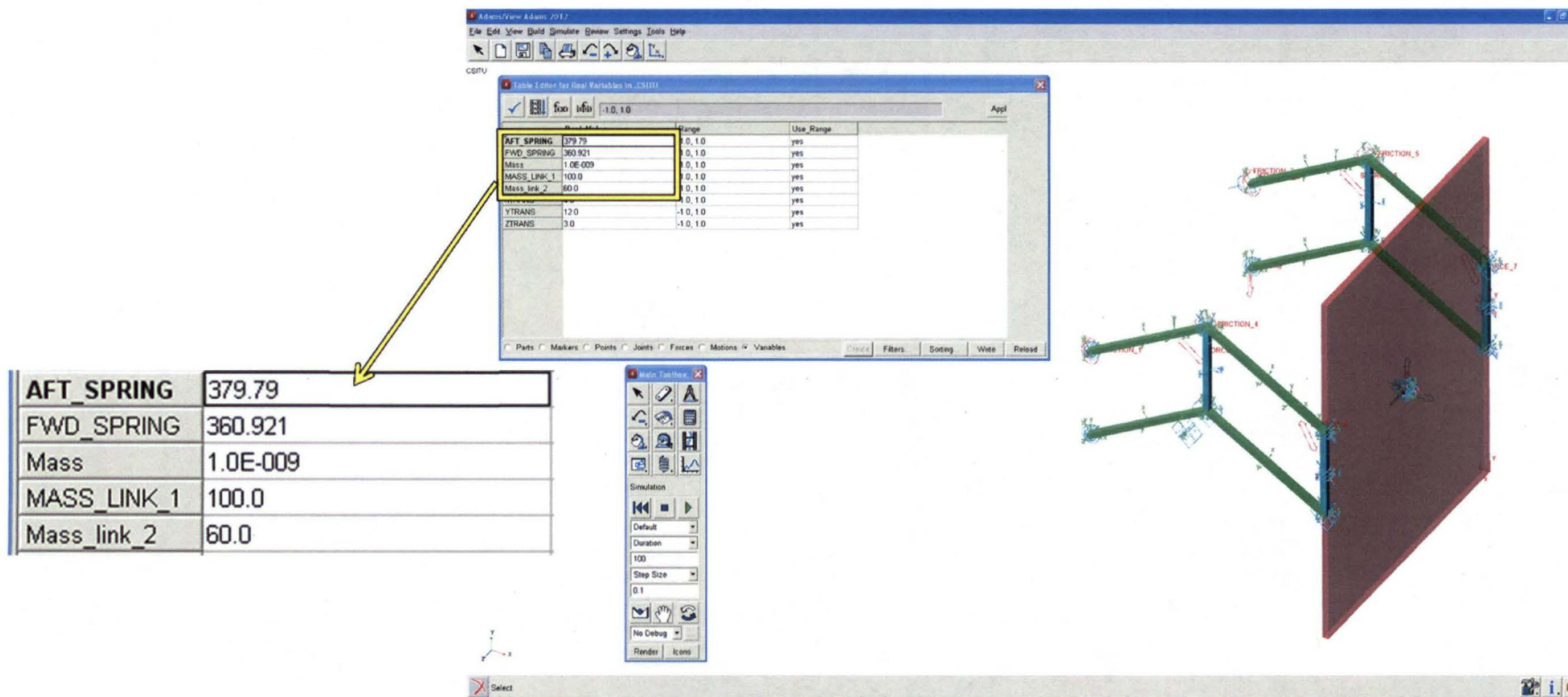


- Arrows represent spring force direction vector

Spring Rate

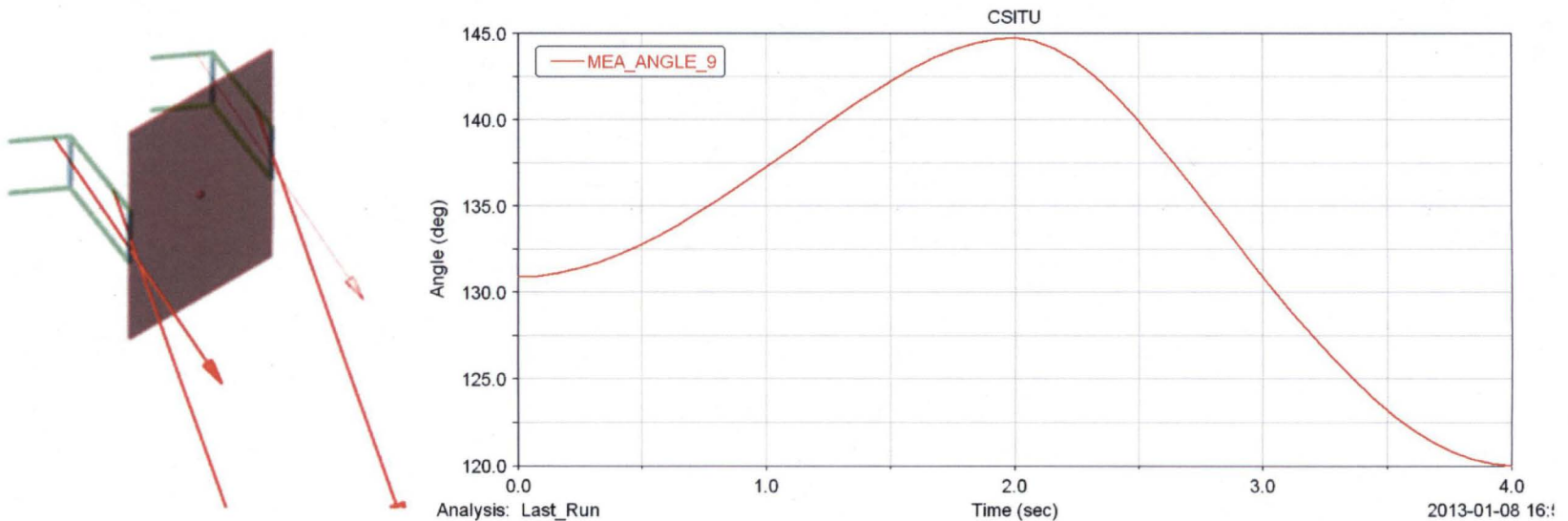
Dynamic model created (Adams) to verify hand calculations for the spring rates

The results in Adams verifies calculations are accurate and shows passive balance is obtained



Quantification of mechanism behavior can be easier understood using the Adams post processing feature.

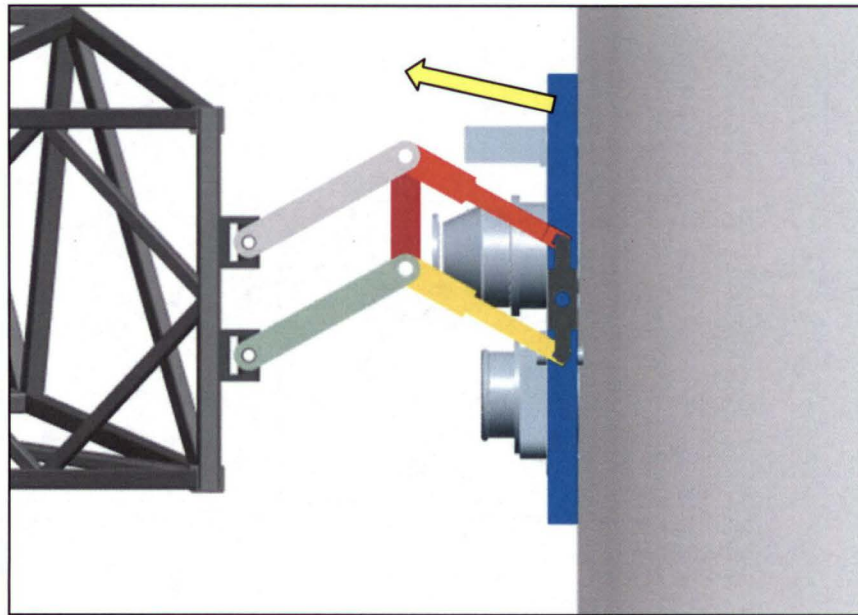
When simulating maximum vehicle excursions, this is useful for determining link angles with respect to time. This feature is also very useful for dynamic force analysis.



Primary Retract Mechanism

The primary release mechanism will employ either a pneumatic or hydraulic cylinder to achieve the 10° plate rotation and 12" retraction

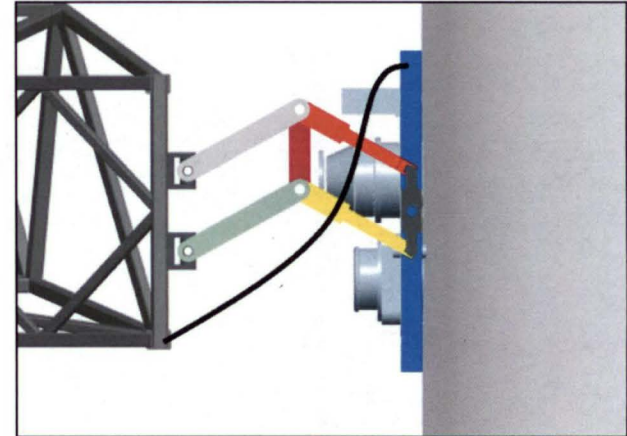
- Mechanism can accommodate this system



Passive Secondary Release Mechanism

- Static wire rope attached to bottom of truss
- Wire rope pulls lever arm to create a separation force between plate and vehicle
- The maximum vehicle rise before actuation is 12.5"

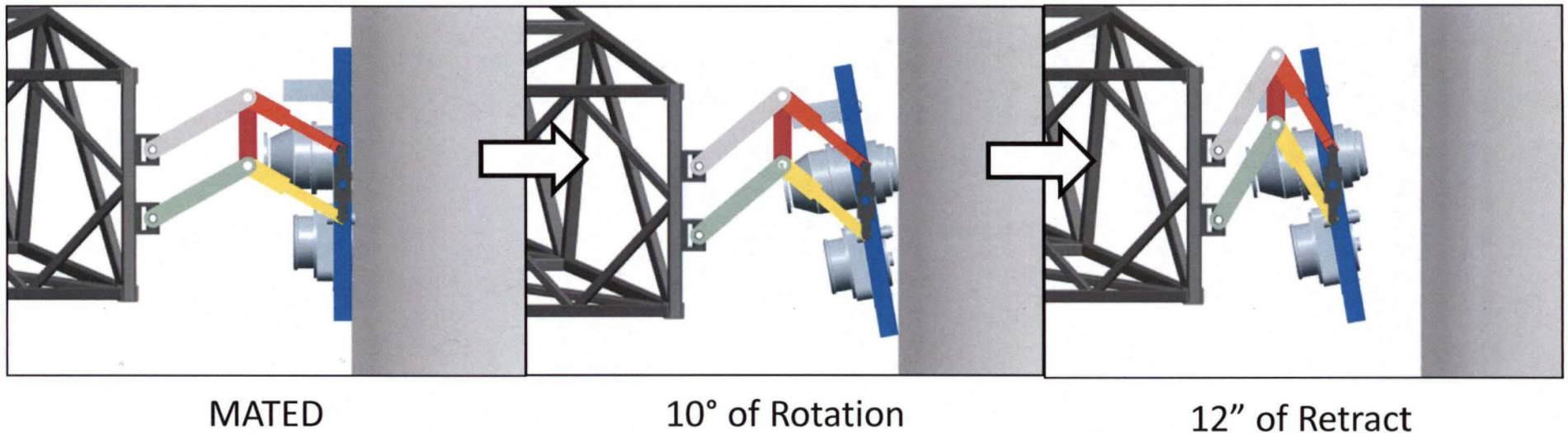
- Compliance mechanism can accommodate all aspects of the secondary release mechanism



Primary Release Dynamics

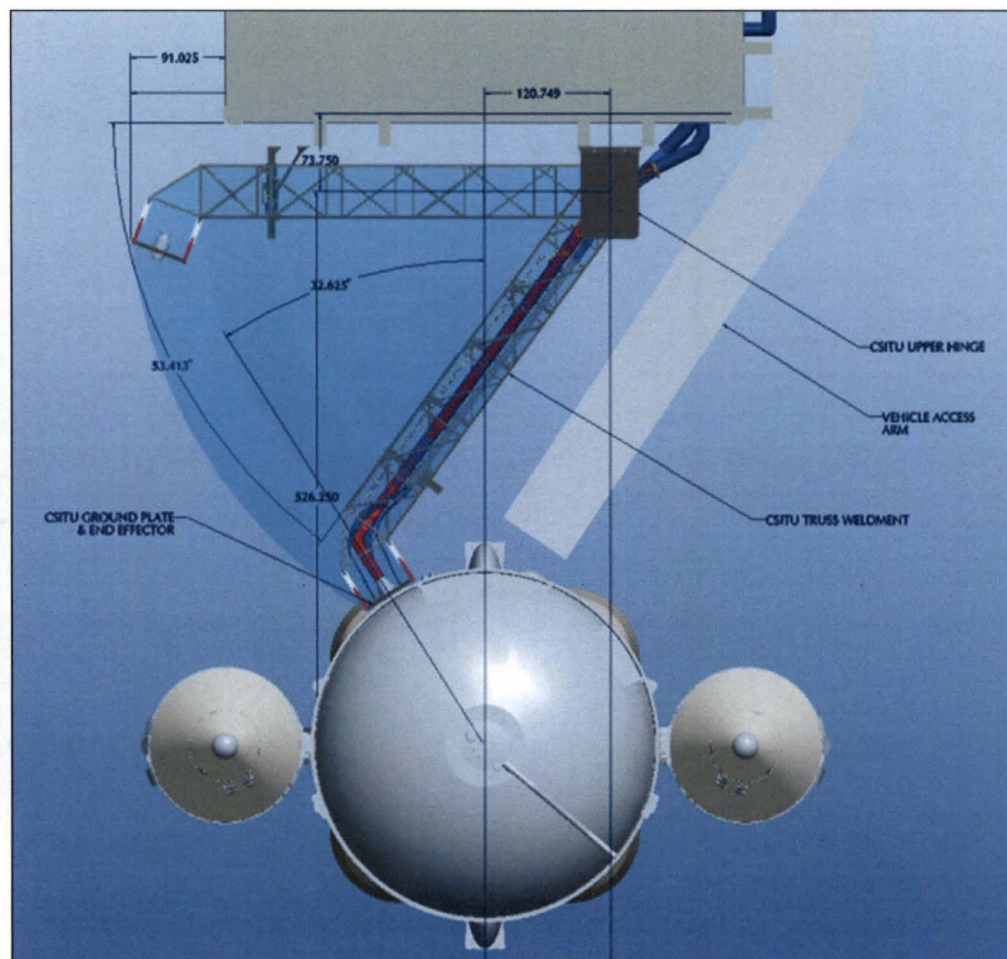
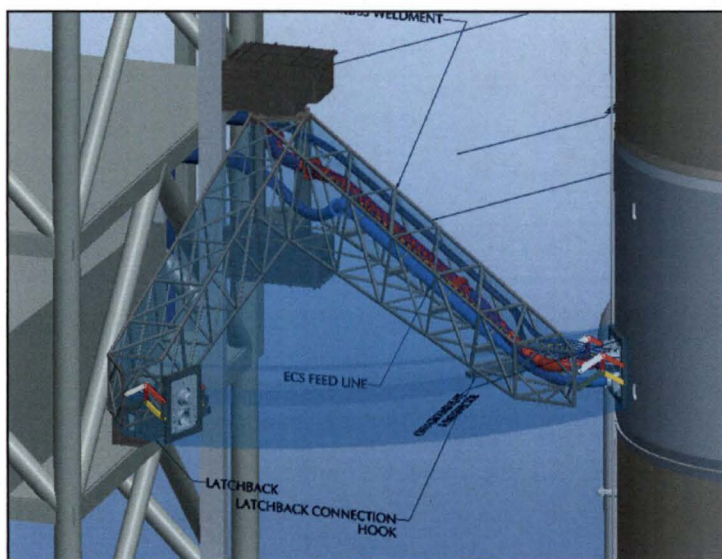
The sequence below depicts the primary release mode for the compliance

Note, springs have not yet been placed



- Mechanism can achieve design goal for 10° plate rotation and 12" retract

Vehicle Integration and Launch (VIL) CSITU 30% Design Review, 1/16/2013



Mature design to 60% level

- **Detailed Design**
 - Member shapes/size
 - Spring configuration/pulley configuration
 - Spring deflection distances
 - Determine where to place side-to-side reaction forces
- **Analysis**
 - Factor in stiffness of hoses
 - Redo hand calculations to include supporting members
 - Spring rates
 - Determine required force to react side-to-side loading
 - Stress Analysis

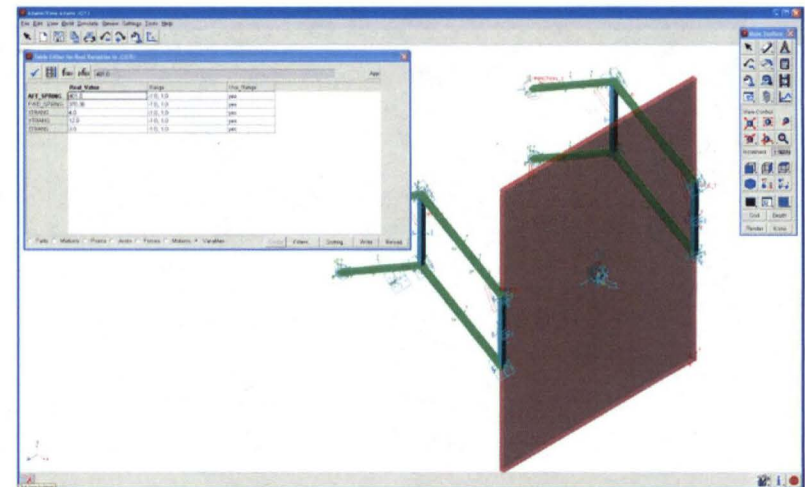
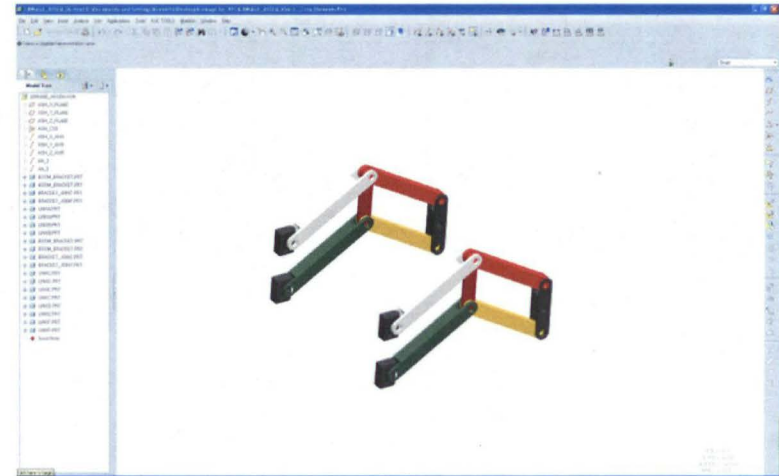
**Increased proficiency in
Pro/Engineer, Pro/E Mechanism,
Adams**

Increase in umbilical knowledge

- Functionality
- Varying configurations
- Design considerations

**Better understanding of the work
going on at KSC**

**Contacts from many organizations
around center**



Questions?

Project as of Today

